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Title: A Brief Tutorial Introduction to Model Verification & Validation for Structural Dynamics

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A Brief Tutorial Introduction to Model Verification & Validation for Structural Dynamics

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Abstract

This presentation provides a brief overview of the verification and validation (V&V) process as applied to structural dynamics. It presents the motivation for V&V as a method of establishing credibiltiy for computational simulations and describes the hierarchical approach to V&V. It covers the steps in the V&V process including definition of the validation study, code verification, calculation verification, sensitivity analysis, uncertainty analysis, validation experiments, test-analysis correlation, model revision & updating, and estimation of predictive accuracy.

Credibility is a Crucial Characteristic of Engineering Calculations

- Engineering decisions are becoming continually more dependent on the results of computational analysis
  - Cost of computations continually dropping
  - Cost of experimentation continually increasing
  - Design cycle time continually shortening
  - Many global response tests prohibitive ($$ and/or politics)
- Computational analyses must have demonstrable ***credibility***

- ***Verification and Validation*** (V&V) is a systematic process for quantifying the credibility of computational results via the assembly of ***evidence,*** as well as defining the limits of that credibility
  - For a particular application
  - Over a particular range of operating conditions and configurations
  - To a specified level of accuracy

Definitions of Verification and Validation

- Verification

  Code Verification—Process of determining that the computer code is correct and functioning as intended.

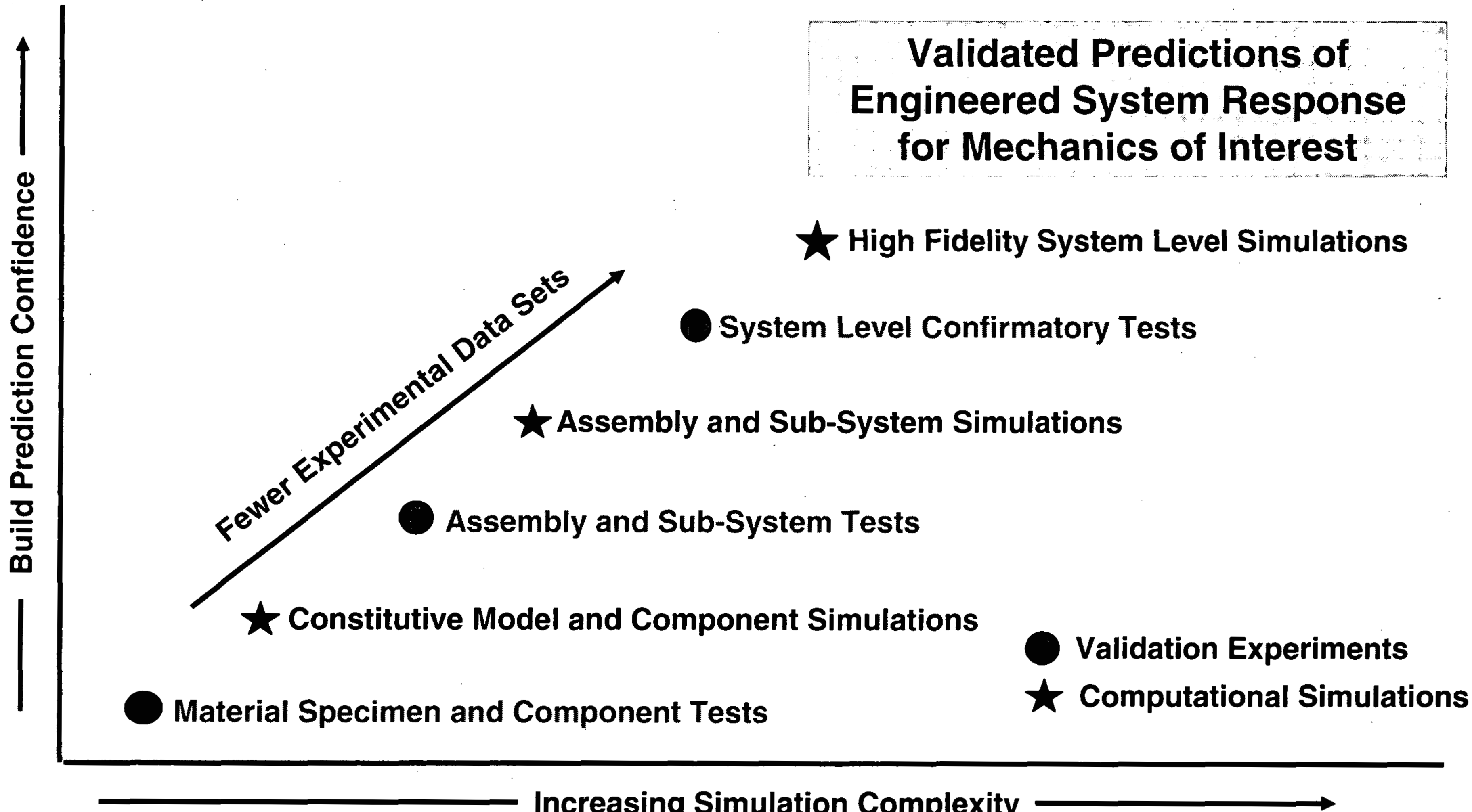
  » "Solving the equations correctly" [1]

  Calculation Verification—Process of determining the solution accuracy of a particular calculation.

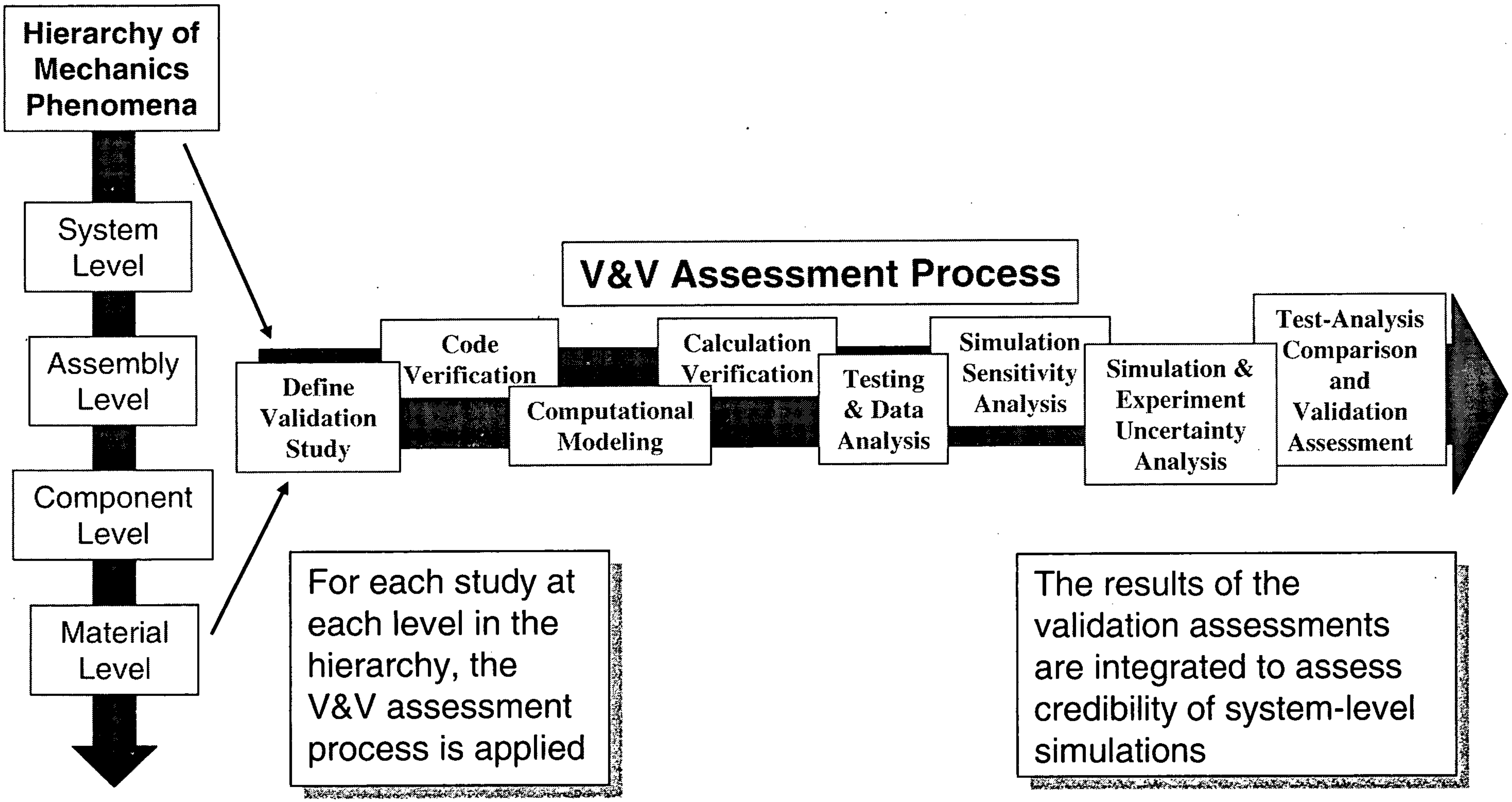
  » Also: "Showing that the solution is independent of the mesh"

- Validation
  - Process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.
    - » "Solving the correct equations" [1]
    - » "Fit for purpose" [2]
    - » "The substantiation that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended applications of the model" [3]

Prediction Credibility of Complex Physical Systems can be Assessed via Hierarchical Approach



Hierarchical Approach and V&V Assessment Process



Definition of Validation Study

- Key physical phenomena of interest
  - Phenomena Identification and Ranking Table (PIRT)
- Response features of interest
  - Characteristics of the model response that are relevant to the application
- Model parameters and parameter domain of interest
- Validation assessment and adequacy criteria
  - Clearly define the requirements of the "customer" or "decision maker"
  - E.g. the results from the computation will be used for a loads analysis – how accurate do the results have to be? – how good is good enough?

Defining the characteristics of the V&V study a priori will improve the credibility of the study by avoiding any appearance of "revisionism"

Example of Identifying Key Physical Phenomena

Results of "qualitative" sensitivity analysis based on engineering judgment can be clearly represented using a Phenomena Identification and Ranking Table (PIRT)

System-Level PIRT for System Mechanical Shock Response

Phenomenon	Importance to Responses of Interest	Initial Simulation Confidence
Shock Transmission – Fwd Joint	HIGH	MEDIUM
Shock Transmission – Aft Joint	HIGH	LOW
Shock Transmission – Container	HIGH	MEDIUM
Fracture of Internal Components	HIGH	LOW

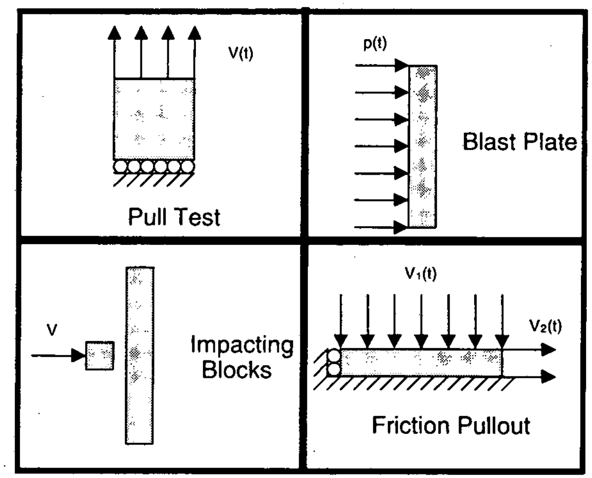
Assembly-Level PIRT for Forward Joint Shock Response

Phenomenon	Importance to Responses of Interest	Initial Simulation Confidence
Elastic Response of Aluminum	HIGH	MEDIUM
Elastic Response of Titanium	HIGH	LOW
Impact of Threaded Interfaces	HIGH	MEDIUM
Impact of Smooth Interfaces	HIGH	LOW
Impact of Threaded Interfaces	HIGH	MEDIUM
Impact of Smooth Interfaces	HIGH	LOW

Later, quantitative sensitivity analysis will be used to further refine the rankings

Code Verification

- "Thorough" verification of computer code is a responsibility of the code developer – documentation should be provided to the end users
- "End Users" have responsibility to spot-check code with test problems relevant to their mechanics of interest
- Selection of appropriate "unit problems"
  - Examples:
    Sliding friction, high-velocity impact, etc.



Problem	Abaqus	Pronto	Dyna3D
Pull Test	10^{-4}%	10^{-4}%	2×10^{-3}%
Blast Plate	5×10^{-3}%	4×10^{-3}%	4×10^{-3}%
Impacting Blocks	0.2%	13%	3%
Friction Pullout	0.9%	0.9%	[redacted]

Numerical Errors Obtained with Tri-Lab Verification Suite #1.

Calculation Verification

- **Mesh convergence can theoretically be verified using *error estimators*.**

$$u^{True} = u(h) + \underbrace{\alpha h^{p}}_{\text{Order of the convergence is } p.} + O(h^{p+1})$$

- **In practice, the calculation is performed twice using two meshes (one is called the *coarse mesh*, one is called the *fine mesh*) and solutions are compared.**

- **Mesh convergence rate depends on the definition of the response feature of interest.**

Calculation Verification: Richardson Extrapolation

- **Perform one computation with a coarse mesh whose size is denoted h_C. The solution $u(h_C)$ is:**

$$u^{True} = u(h_C) + \alpha h_C^p + h.o.t.$$

- **Perform a second computation with a refined mesh whose size is denoted h_F. The solution $u(h_F)$ is:**

$$u^{True} = u(h_F) + \alpha h_F^p + h.o.t.$$

- **Combining the two equations, an estimation of the "true-but-unknown" solution can be obtained:**

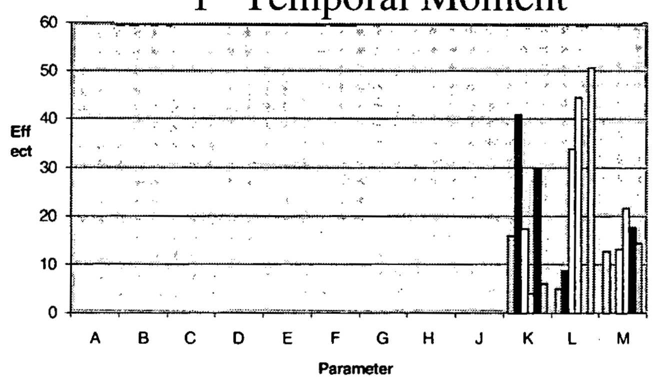
Study the convergence of u^{True} as a function of r.

$$\left\{ u^{True} \approx \frac{r^p u(h_F) - u(h_C)}{r^p - 1} \right. \quad \text{where} \quad r = \frac{h_C}{h_F}$$

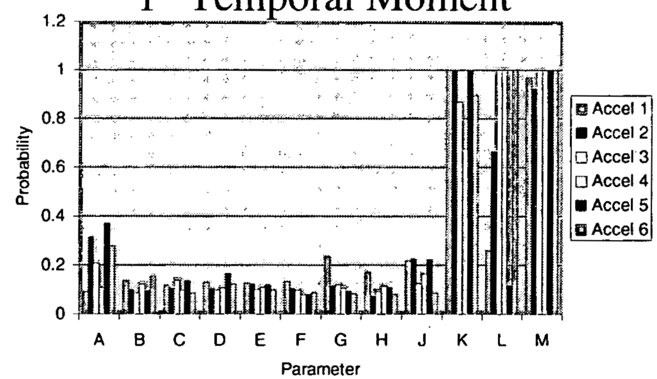
Sensitivity Analysis & Parameter Screening

- Which simulation input parameters have the most significant influence on the response features of interest?
  - Example Parameters: material properties, compliance and energy loss characteristics of joints, preload, friction coefficients, load magnitudes, boundary stiffnesses, etc.)
- Global sensitivity analysis used to rank relative importance of the parameters
  - Unimportant parameters eliminated from further study
  - Important parameters used to define domain of interest for validation

ANOVA Effects for 1st Temporal Moment



Bayesian Effects for 1st Temporal Moment



Uncertainty Analysis / Uncertainty Quantification

Uncertainty analysis, as applied to mode validation, is concerned with these main issues:

- Computational simulations:
  - Uncertainties on simulation input parameters
  - Propagation of input parameter uncertainty to response features
  - Uncertainties in form of mathematical model
- Experimental measurements:
  - Test-To-Test repeatability
  - Unit-to-Unit variability
  - Separating systematic and random effects
- Test/analysis Correlation:
  - Comparative metrics in the presence of uncertainty
  - Attributing observed uncertainty to component sources

Validation Experiments

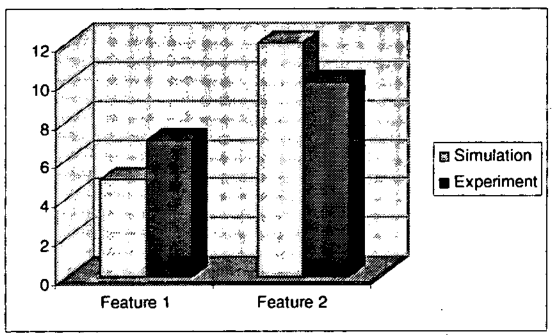
- Experiments conducted for the purposes of model validation are usually different from experiments conducted for other purposes, e.g. system qualification
- Important to know the details of what was tested
  - Test data is the "right answer," but what was the question?
  - Parameter settings (e.g. environmental variables)
  - Loads & boundary conditions
- "Verify" the test
  - Linearity, reciprocity, stationarity, damping & mode separation assumptions, averaging

Test-analysis Correlation

- Test-analysis Correlation (TAC) is the process of assessing the consistency—or lack-of-consistency—between the measured and predicted responses.

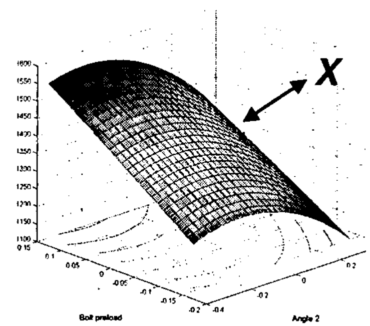
Discrete Point to Discrete Point

$$E = \left\| \left(f_p - f_e \right) \right\|_2$$



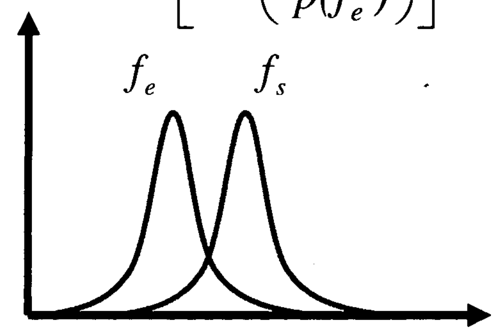
Discrete Point to Response Surface

$$E = \min\left(\left\| f_e - S_p \right\|_2 \right)$$



Distribution to Distribution

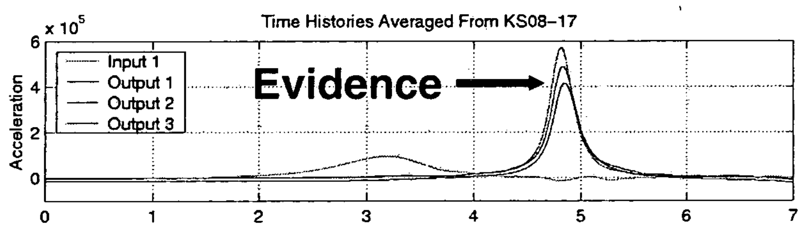
$$E = E\left[\log\left(\frac{p(f_s)}{p(f_e)} \right) \right]$$

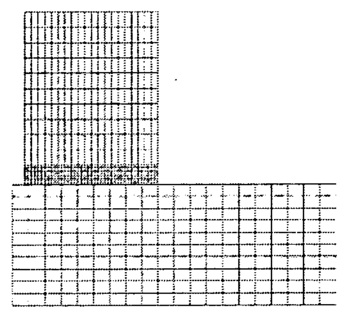


- Validation metrics assess the "error" between measured and simulated features.
- E.g. Modal frequency error, modal assurance criterion, statistical tests

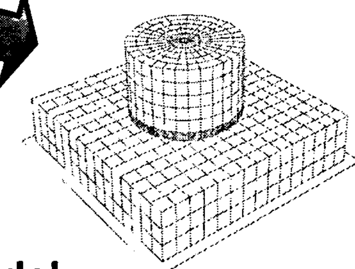
Model Revision & Updating

- Changes brought to model to improve predictive accuracy
- Parametric revisions – changes to parameter values
  - Typically optimize parameter values to minimize some test/analysis metric - a.k.a. model updating, model calibration
  - **Calibration of parameter values is a model development activity, and does not constitute validation**
- Conceptual revisions – changes to model form
  - Adding or removing contact, changing energy loss mechanism, changing form of boundary condition, 2-D vs. 3-D modeling





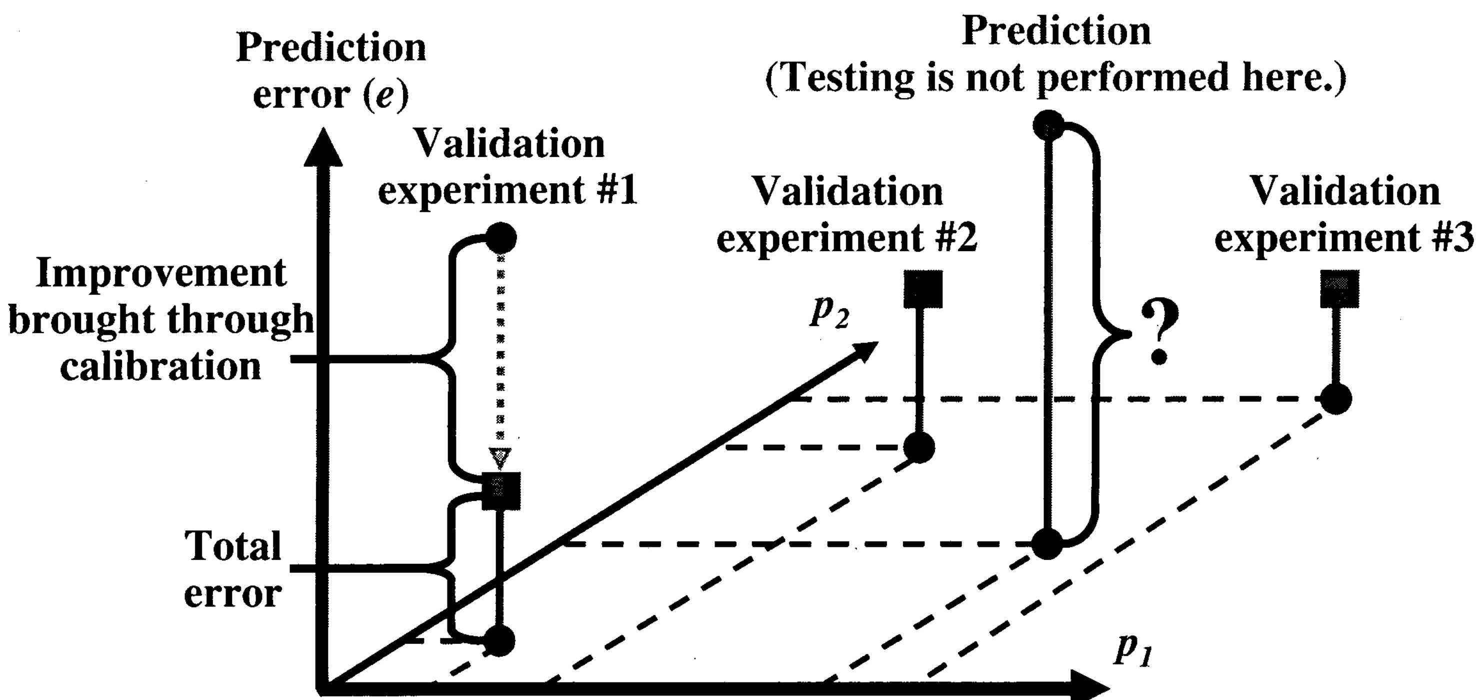
2D model (symmetric)



3D model (with impact angles)

Predictive Accuracy Estimation

- The components of *predictive accuracy estimation* are the model $y = \mathrm{M}(p)$, design space, measurements y^{Test} and prediction error $e = \|y^{Test} - y\|$.



Summary

- ***Verification and Validation*** (V&V) is a systematic process for quantifying the credibility of computational results via the assembly of ***evidence,*** as well as defining the limits of that credibility
  - For a particular application
  - Over a particular range of operating conditions and configurations
  - To a specified level of accuracy
- Prediction credibility of complex physical systems can be assessed via hierarchical approach
- Defining the characteristics of the V&V study a priori will improve the credibility of the study
- Important to know the details of what was tested
- Calibration of parameter values is a model development activity, and does not constitute validation
- Document, document document -> clear and concise documentation is a key to credibility

References

1. Roache, P.J., 1998, *Verification and Validation in Computational Science and Engineering*, Hermosa Publishers, Albq, NM.
2. Ewins, D.J., International Conference on Structural Dynamics Modelling: Test, Analysis, Correlation and Validation, Madeira Island, Portugal, 3-5 June 2002
3. Schlesinger, S., et al., 1979, "Terminology for Model Credibility," Simulation, 32 (3), 103-104.